

# **Soil moisture determination using reflected Global Positioning System (GPS) signals**

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***AirSC Technical talk  
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# Agenda

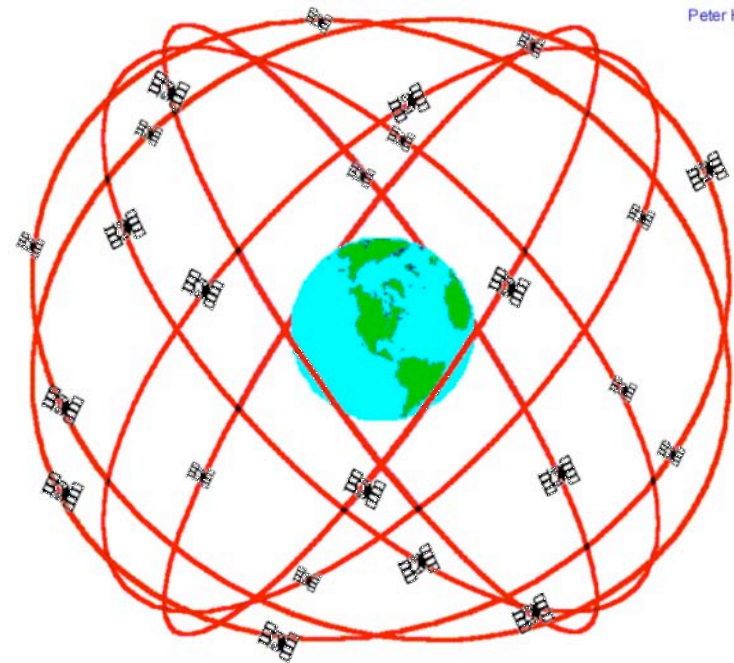


- What is GPS?
- What is soil moisture?
- GPS, soil moisture and aircraft safety
- Microwave remote sensing of soil moisture
- Theory
  - Dielectric constant
  - Sensing depth
- Hardware: GPS reflectometer
- Characteristics of the data
- Methods and analysis
  - Location of reflection points
  - Reflectivity over water
  - Reflectivity over land
  - Permittivity comparisons
  - Soil Moisture
  - Soil type effects
  - Permittivity over the southwest
  - Some limitations
- R dependence on  $m_v$
- Conclusion
- Open forum

# What is GPS?



- Global Positioning System
- 24-satellite world-wide navigation system
- 5-8 are satellites visible from any point at all times
- Navigation message is modulated into two microwave carriers :
  - L1 at 1575.42 MHz
  - L2 at 1227.60 MHz
- Message is transmitted 24/7
- A GPS receiver can compute:
  - Position
  - Time

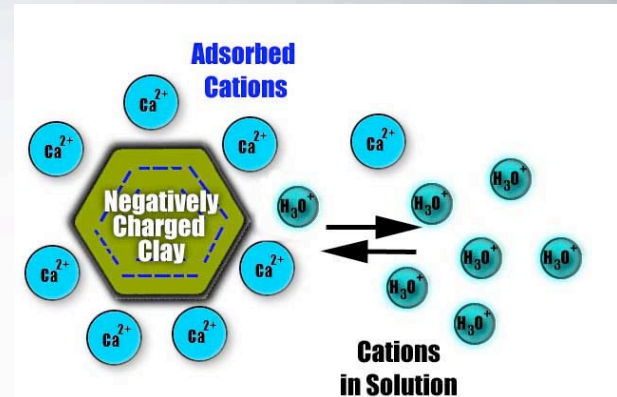


Peter H. Dana 9/22/98

# What is soil moisture?



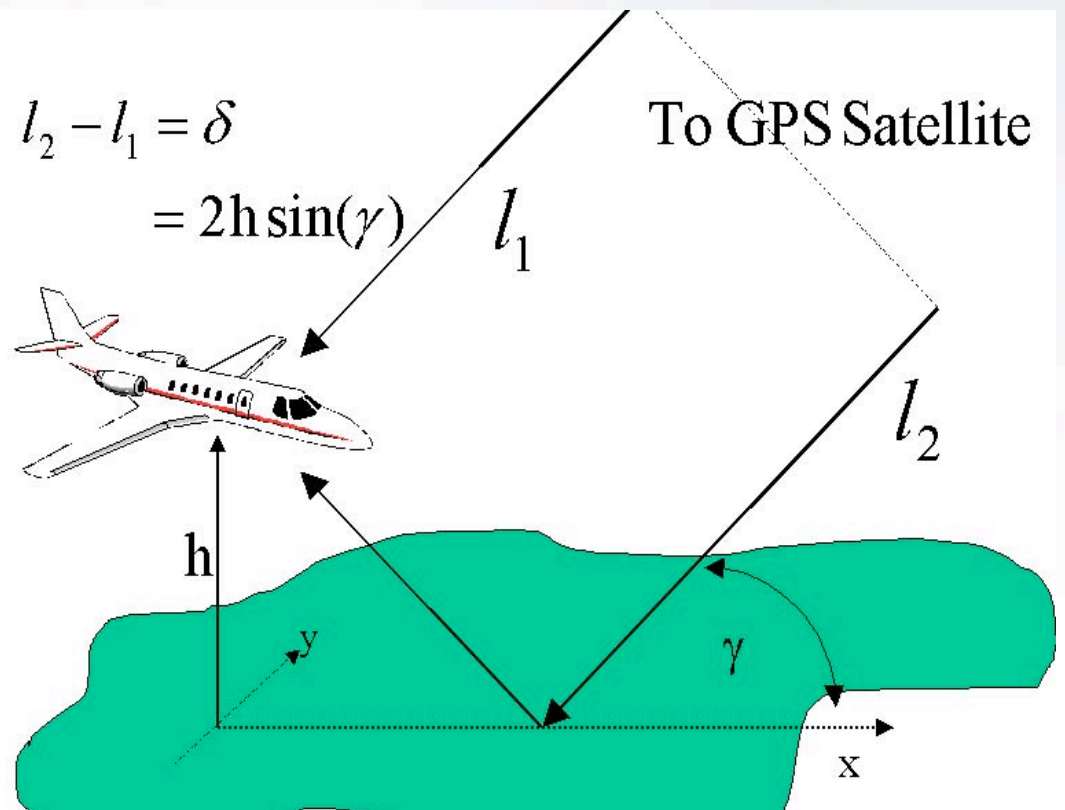
- The retention of water in the soil
- Formed by particles of soil, water, and air
- Water in the soil is divided into
  - Bound water
  - Free water
- Bound water is tightly held by soil
- Free water is available to plants
- Soil moisture forms part of the water cycle as humidity by
  - Direct evaporation
  - Plant transpiration
- Better measurements improve the prediction of
  - Weather
  - Floods
  - Wild fires



# GPS-soil moisture-aircraft safety



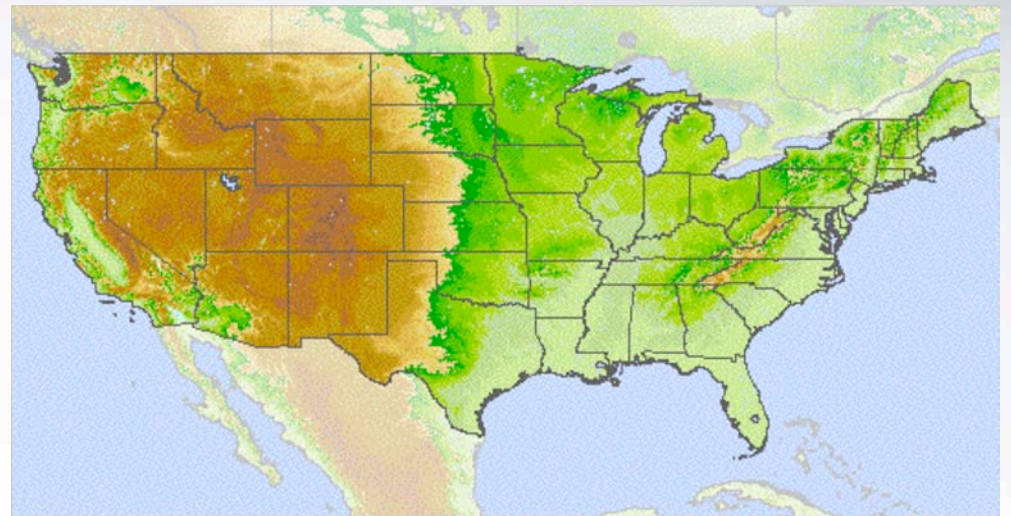
- GPS definition of soil moisture : “soil moisture is a thin layer of something to reflect from”
- Reflections occur near the surface
- The height  $h$  of point P can be computed with simple geometry
- Elevation is referenced to surface and not mean sea-level
- Errors in reported aircraft elevation are greatly minimized



# Difficulties of application

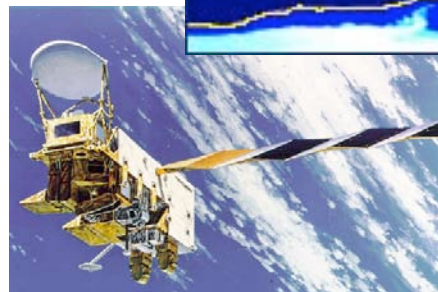
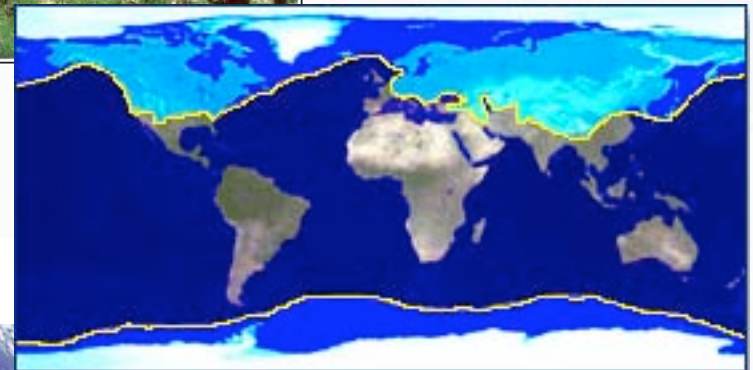


- Reflected GPS power is proportional  $\epsilon_{\text{soil}}$
- $\epsilon_{\text{soil}}$  varies widely over short stretches of land
- Land type variability, vegetation cover, land use, etc change reflections differently
- Coherence of reflected GPS signals depends on surface topography



# GPS remote sensing of soil moisture

- Advantageous due to:
  - Spatial coverage
  - Temporal continuity
- Best measurements at 1-3 GHz
  - Less energy absorbed and reflected by vegetation
  - No side-effects by rain, clouds, snow, etc.
- Only top centimeters of soil are sensed
- Surface roughness scatters the sensing signal
- Deep vegetation absorbs signals



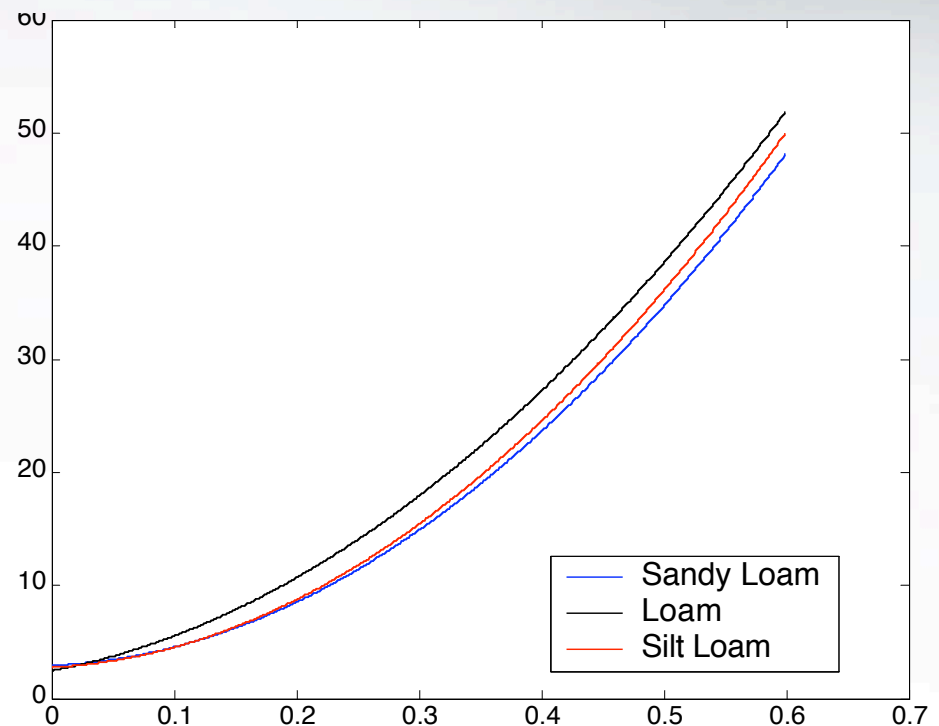
# Dielectric constant of the soil



- GPS remote sensing depends on  $\epsilon_{\text{soil}}$ 
  - $2.5 \leq \epsilon_{\text{soil}} \leq 24$

$$R = \left| \frac{\epsilon_{\text{soil}} \sin \gamma - \sqrt{\epsilon_{\text{soil}} - \cos^2 \gamma}}{\epsilon_{\text{soil}} \sin \gamma + \sqrt{\epsilon_{\text{soil}} - \cos^2 \gamma}} \right|^2$$

- $\epsilon_{\text{soil}}$  in general depends on
  - Bulk density
  - Texture
  - Salinity
  - Moisture
- Soil moisture exercises greatest effect on  $\epsilon_{\text{soil}}$



# Sensing depth



- Penetration depth of any electromagnetic signal in the soil is

- $0.1\lambda \leq \delta_p \leq \lambda$

- Penetration depends on angle of incidence

- Sensing depth

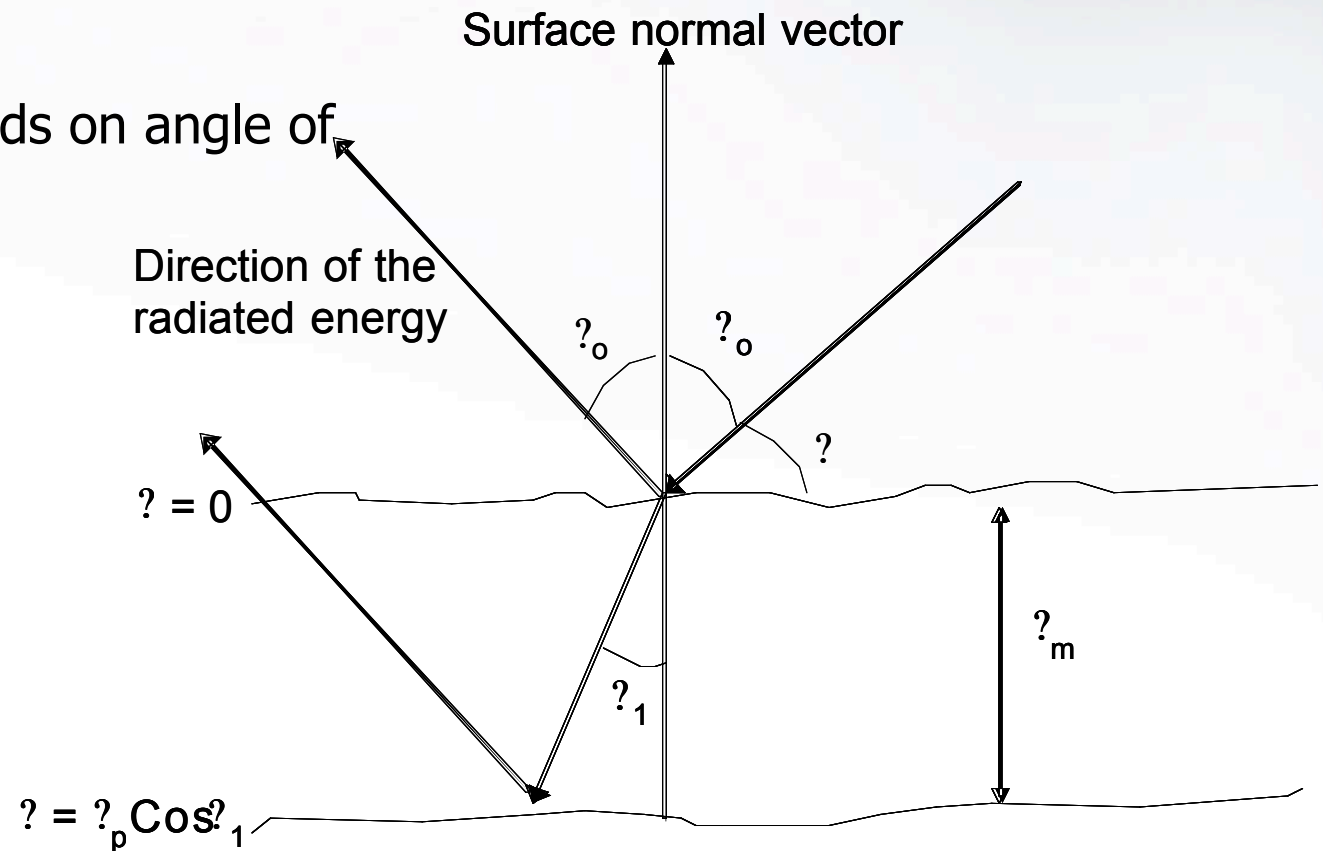
- $\delta_m < \delta_p \cos \theta_1$

- Contribution by

- $1\delta_m$ : 63%

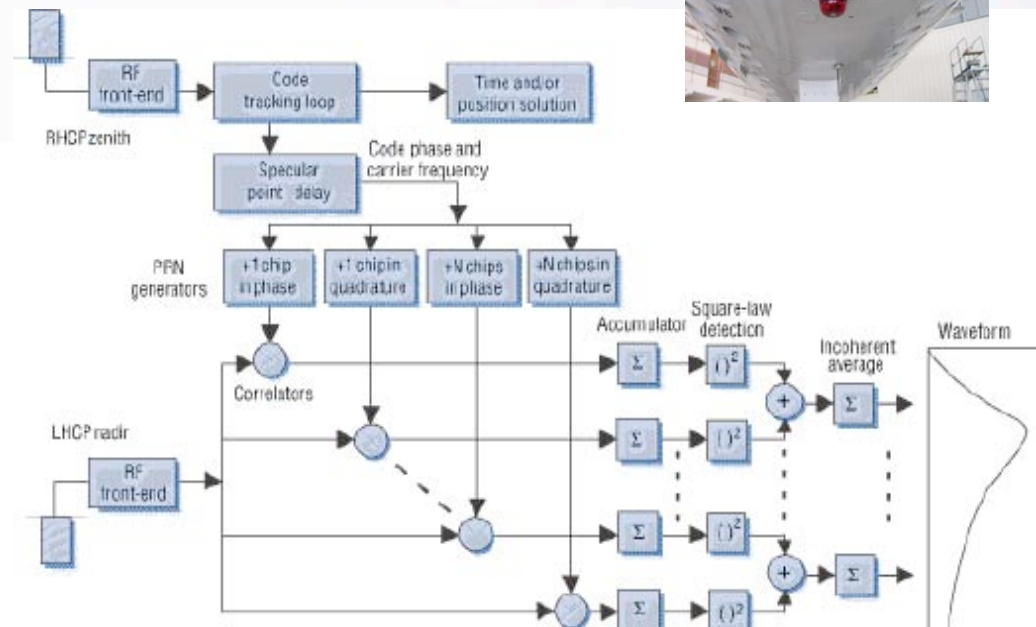
- $2\delta_m$ : 87%

- $3\delta_m$ : 95%



# GPS reflectometer

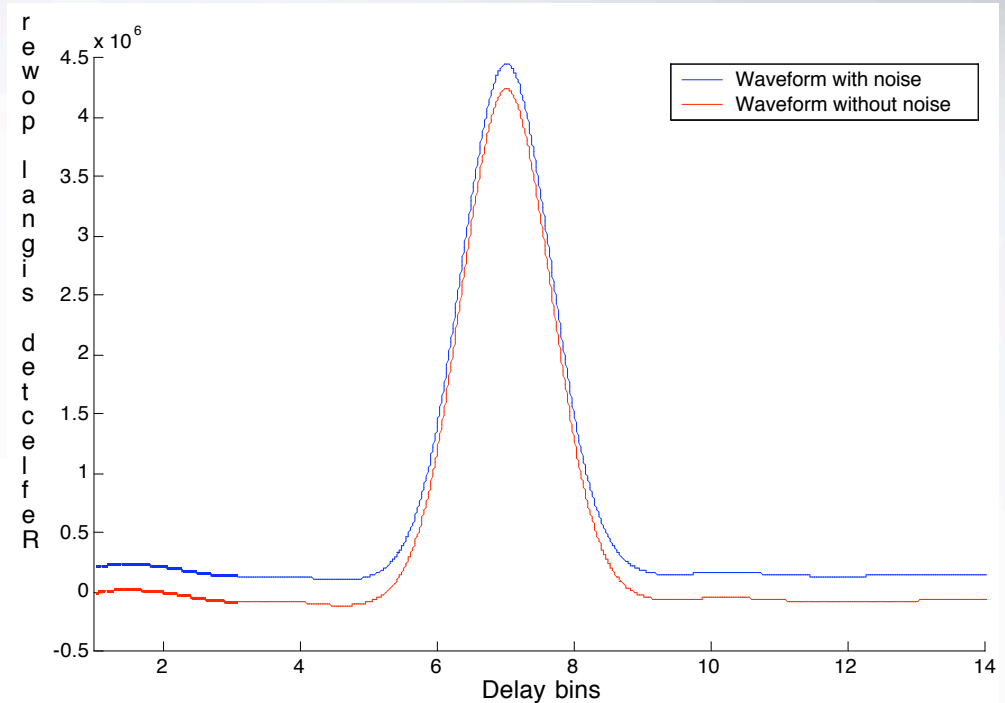
- GPS reflectometer
  - Modified GPS receiver
  - 6 mother channels connected to top antenna
  - 6 daughter channels connected to bottom antenna
  - Consumes  $\sim 9$  watts
- Mother channels collect data directly from satellite
- Daughter channels collect reflected data
- Weighs approximately 5 lbs.
- Can be flown, be stationary, or hand-held



# Characteristics of the data



- Direct data are reported as a single peak values
- Reflected data in 14 discrete delay bins
- $(x,y,z)$  positioning solution available
- Satellite position also reported
- DC value introduced, but easily removable
- Data files linked through tic numbers



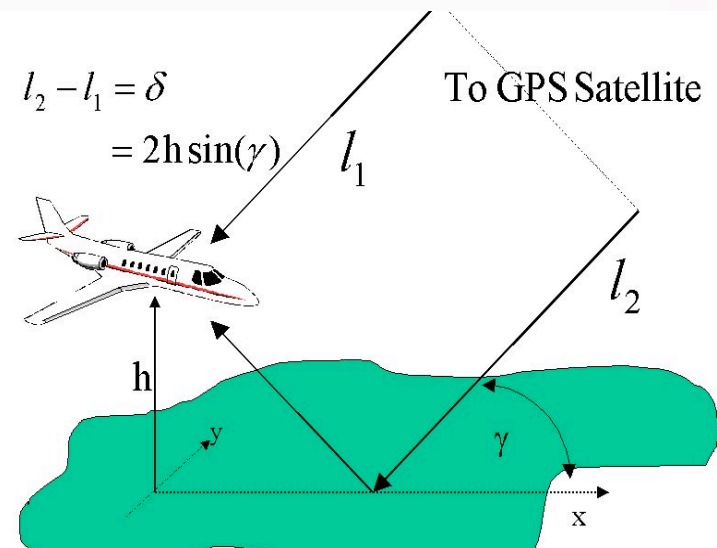
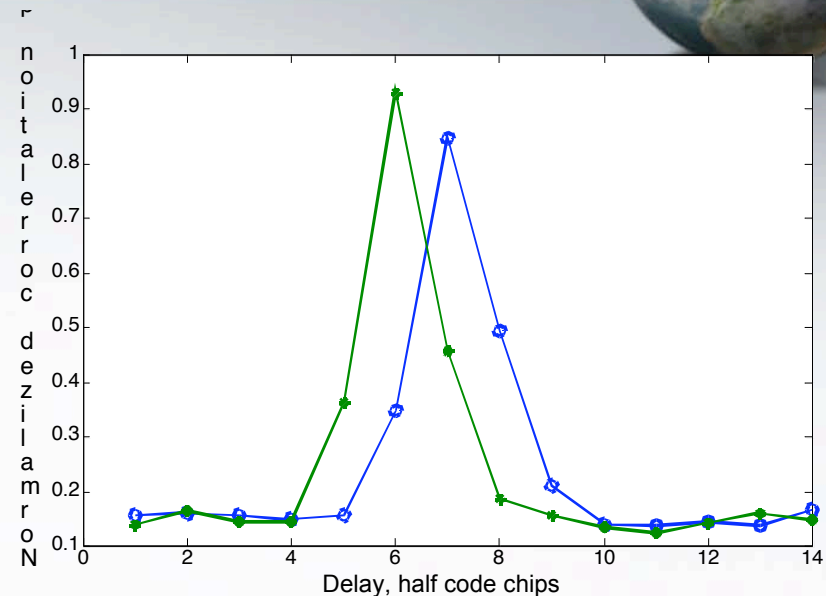
# Methods of sensing with GPS



- Mother channels instruct the daughter to listen for signals after  
 $\delta = 2h \sin \gamma$
- Same signal is recorded by both channels
- Direct data contains multipath effects removed by “smoothing” the data
- Reflectivity computed by

$$R = \frac{\text{Reflected Power}}{\text{Direct Power}}$$

- Reflectivity calibrated to be 63% over water
- Calibration is hardware dependent



# Location of the reflection point



- Reflection point is located slightly off from the receiver

$$\Delta y = \frac{h \cdot \cot \gamma \cdot \cos \varphi}{R_e} \qquad \Delta x = \frac{h \cdot \cot \gamma \cdot \sin \varphi}{R_e \cdot \cos y}$$

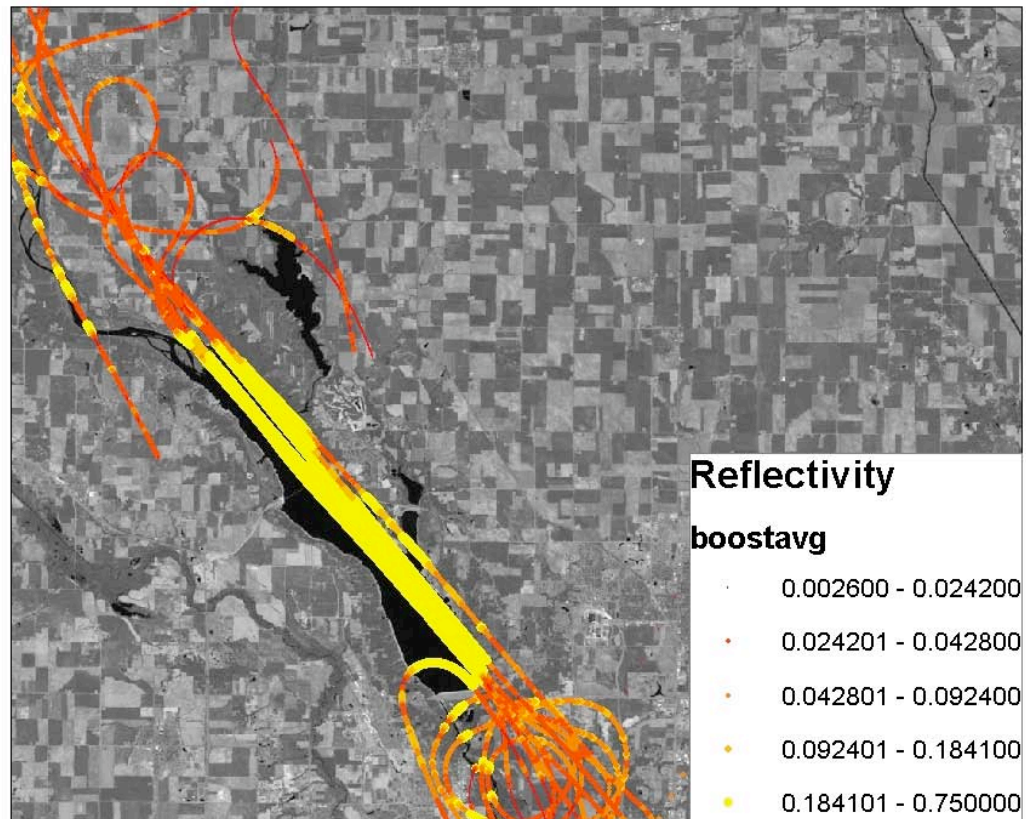
- The reflection point is located at

$$y_r = \Delta y + y \qquad x_r = \Delta x + x$$

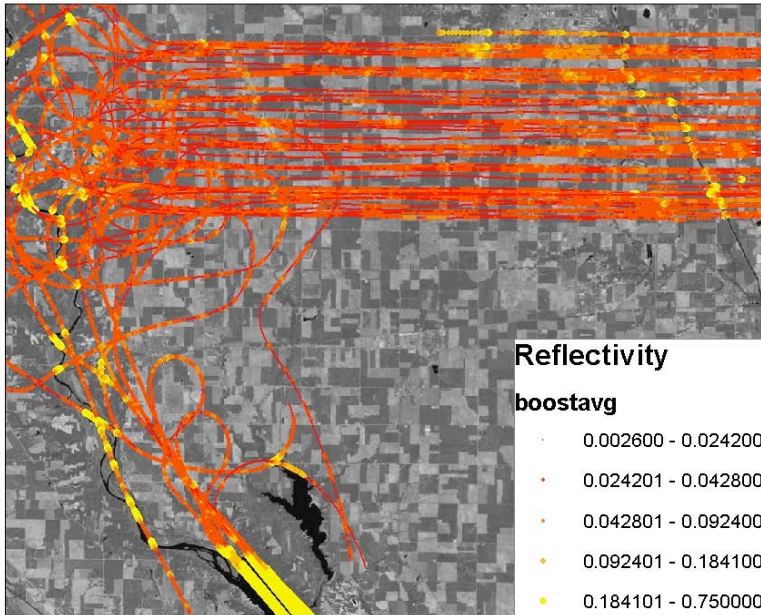
# Reflectivity from water



- Clear correlation with obvious bodies of water
- Maximum reflection from lakes and rivers
- Reflectivity drops dramatically outside the lake

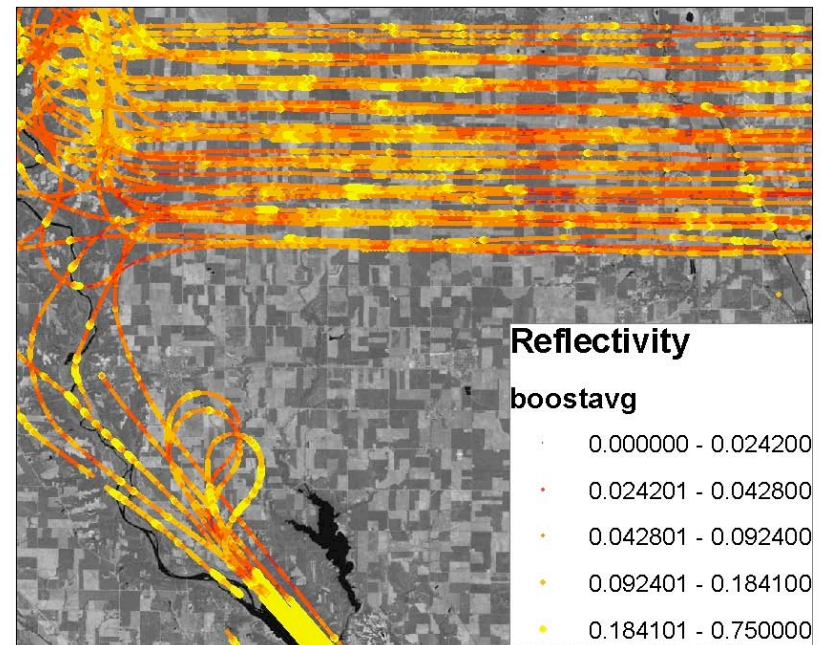


# Reflectivity from land



- Clear increase of reflectivity after the rain

- Land reflectivity variable on the lower region of scale



# Permittivity comparison

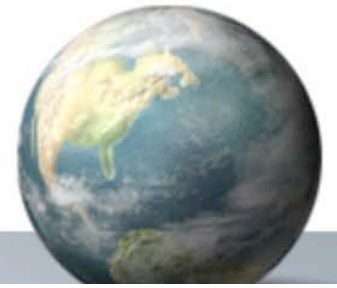


$$\varepsilon^{\alpha}_{soil} = 1 + \frac{\rho_b}{\rho_{ss}} (\varepsilon_{ss}^{\alpha} - 1) + m_v^{\beta} (\varepsilon_{fw} - 1)$$

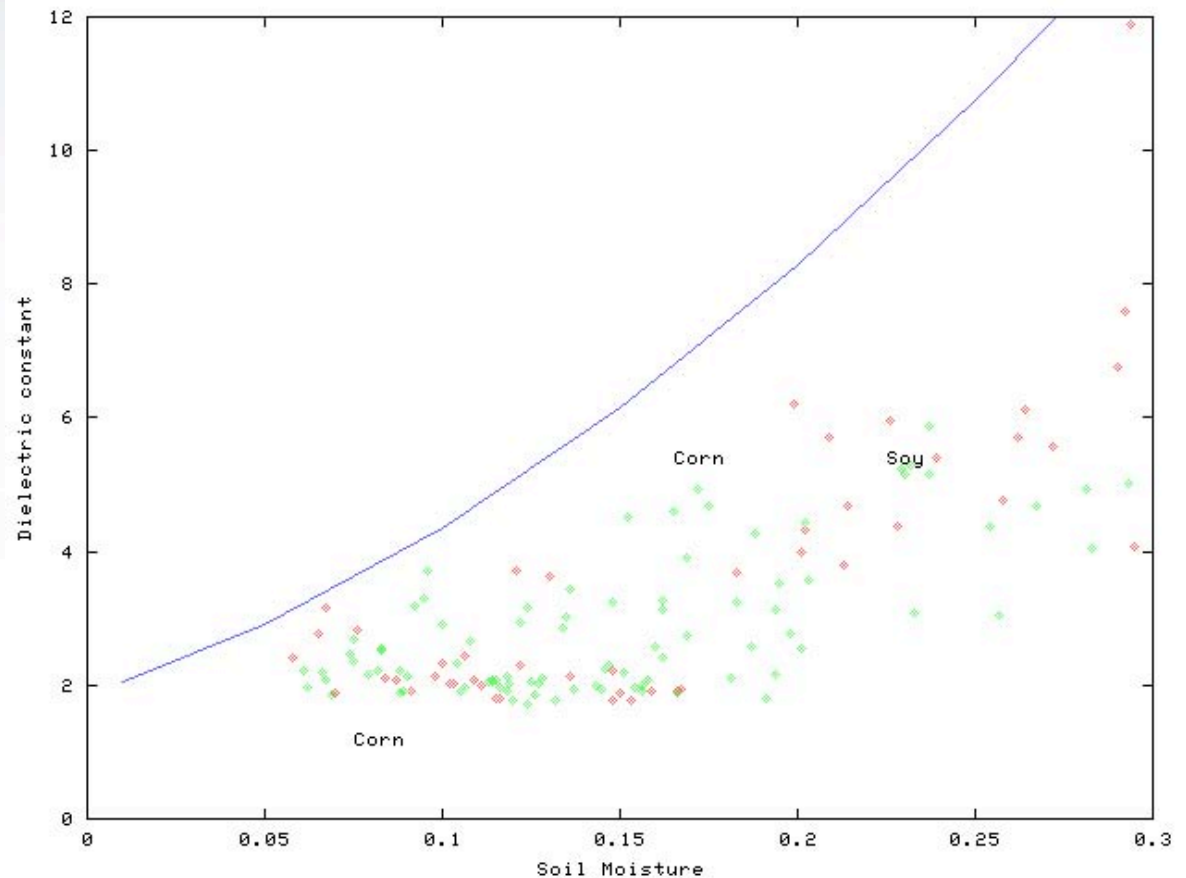
- $\rho_{ss} = 2.5 \text{ g cm}^{-3}$
- $\rho_b$  = soil bulk density
- $\varepsilon_{ss} = 4.7 + j0$
- $\alpha = 0.65$
- $m_v$  = volumetric soil moisture
- $1.0 < \beta < 1.17$

$$\varepsilon^2_{soil} \sin^2 \gamma \left( \frac{1 - \Gamma}{1 + \Gamma} \right)^2 - \varepsilon_{soil} + \cos^2 \gamma = 0$$

# Permittivity comparison



- Theoretical model does not account soil water absorption
- Wilting level of loamy soil = 0.15
- GPS reflections appear to indicate the existence of a wilting level
- Leaf area accounted for



$$\epsilon^{\alpha}_{soil} = 1 + \frac{\rho_b}{\rho_{ss}} (\epsilon_{ss}^{\alpha} - 1) + m_v^{\beta} (\epsilon_{fw} - 1)$$

# Other soils

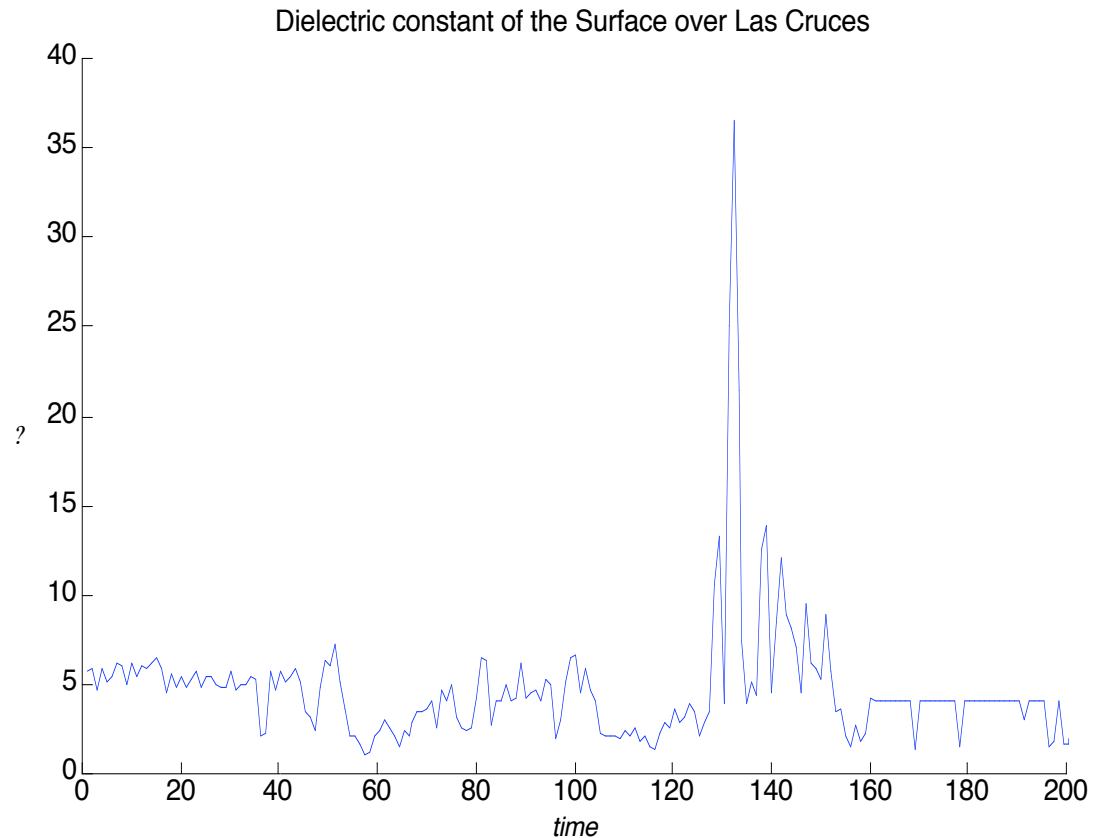


- Soil types differences may observable through GPS reflections under low soil moisture conditions
- Different conditions currently under study
- Sandy soil wilting point = 0.02
- Sandy soil field capacity = 0.3
- Available data from Tifton, Georgia and Las Cruces, New Mexico

# Dielectric constant on the southwest



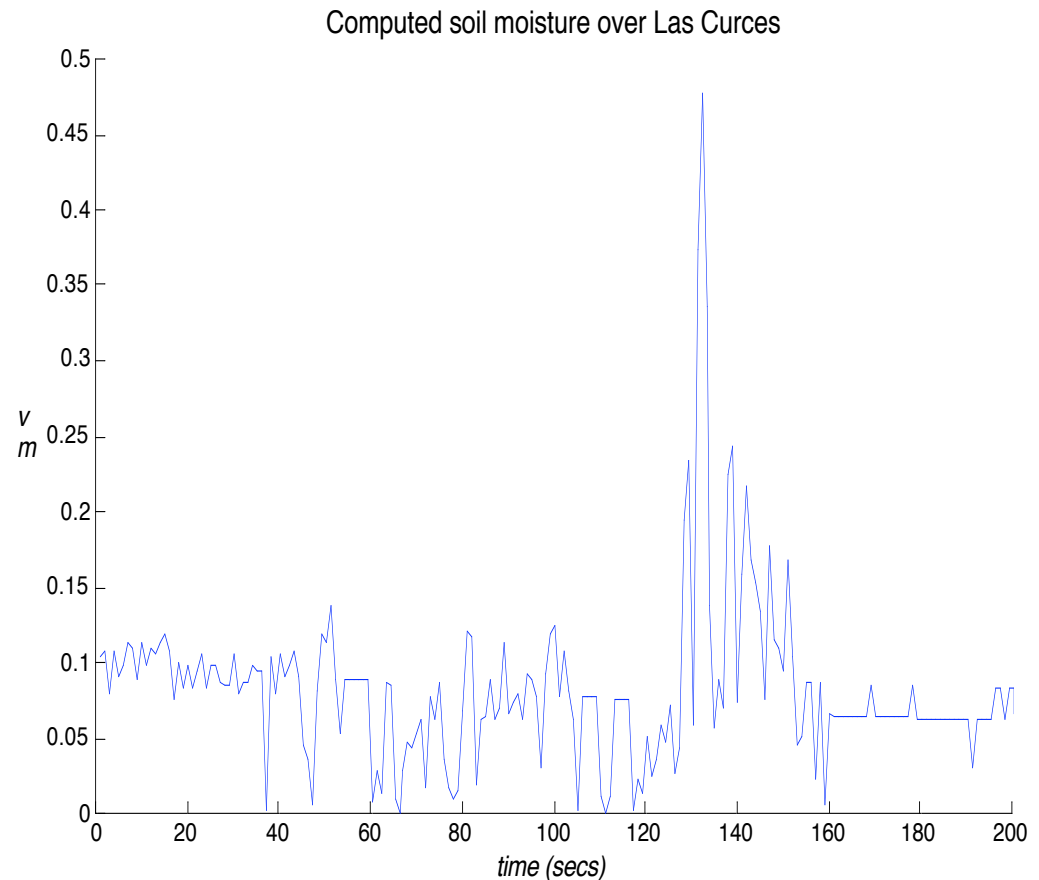
- The  $\epsilon_{\text{avg}} \cong 4.3$
- High values correspond to high soil moisture points, i.e. Rio Grande
- Low values are over arid land
- These values closely match the ones reported in the literature



# Soil Moisture



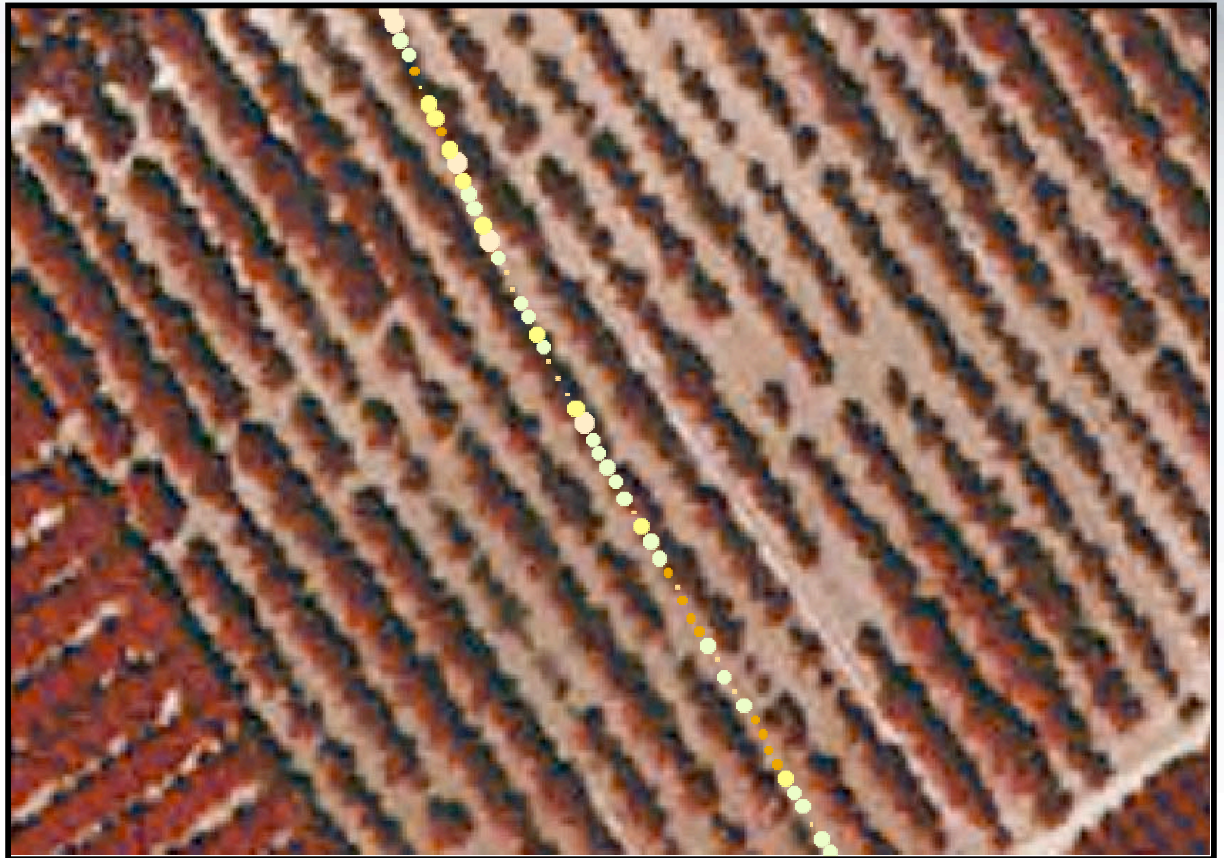
- The maximum value was computed at  $m_v = 59.58\%$
- The max value is reasonable for very wet land
- Minimum value was computed at  $m_v = 0$
- $m_v = 0$  is an extreme case, but acceptable within the errors and limitations of the system



# Reflections over pecan fields



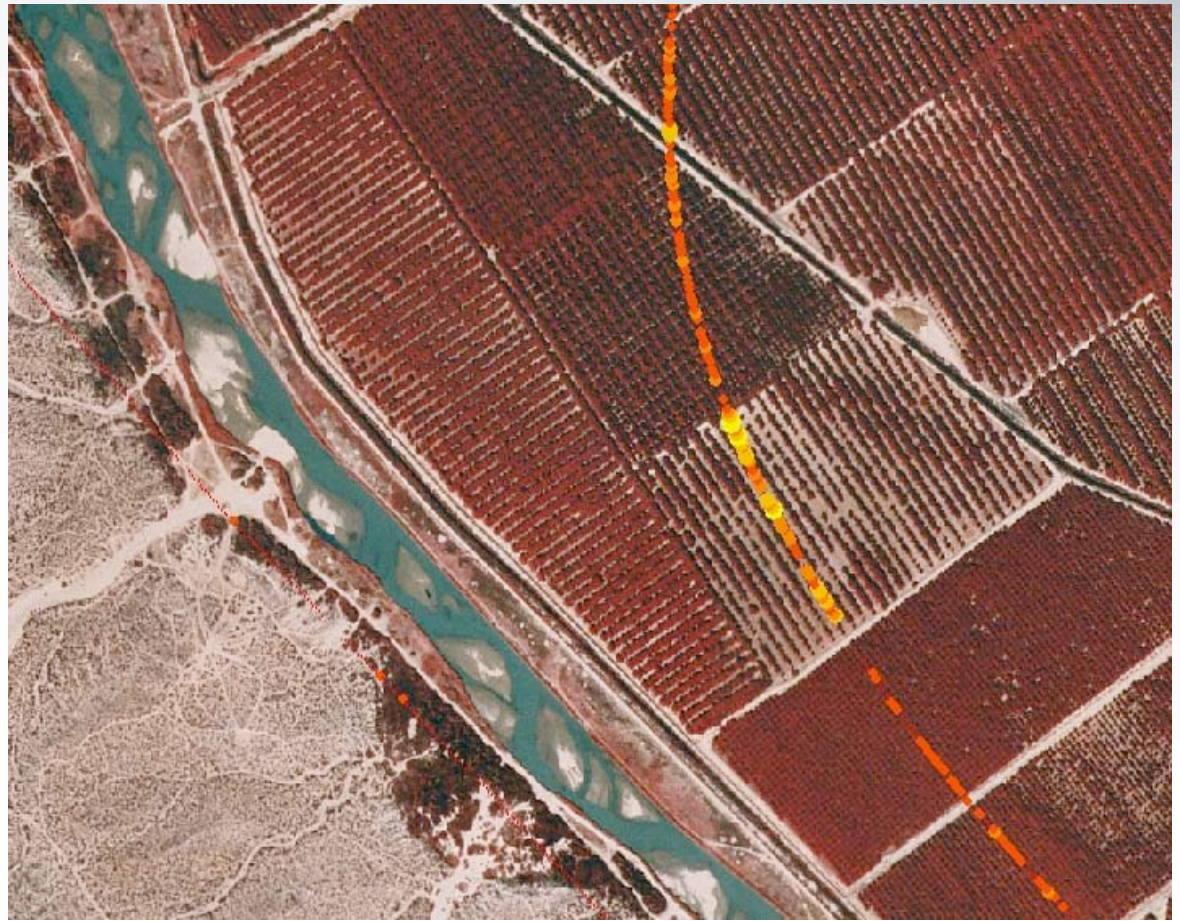
- Reflections over Pecan-tree fields in Las Cruces, New Mexico show limitations
- Signals intermit between strong and weak
- Penetration through open areas
- Absorption or refraction by tree-trunks



# Reflections over arid land



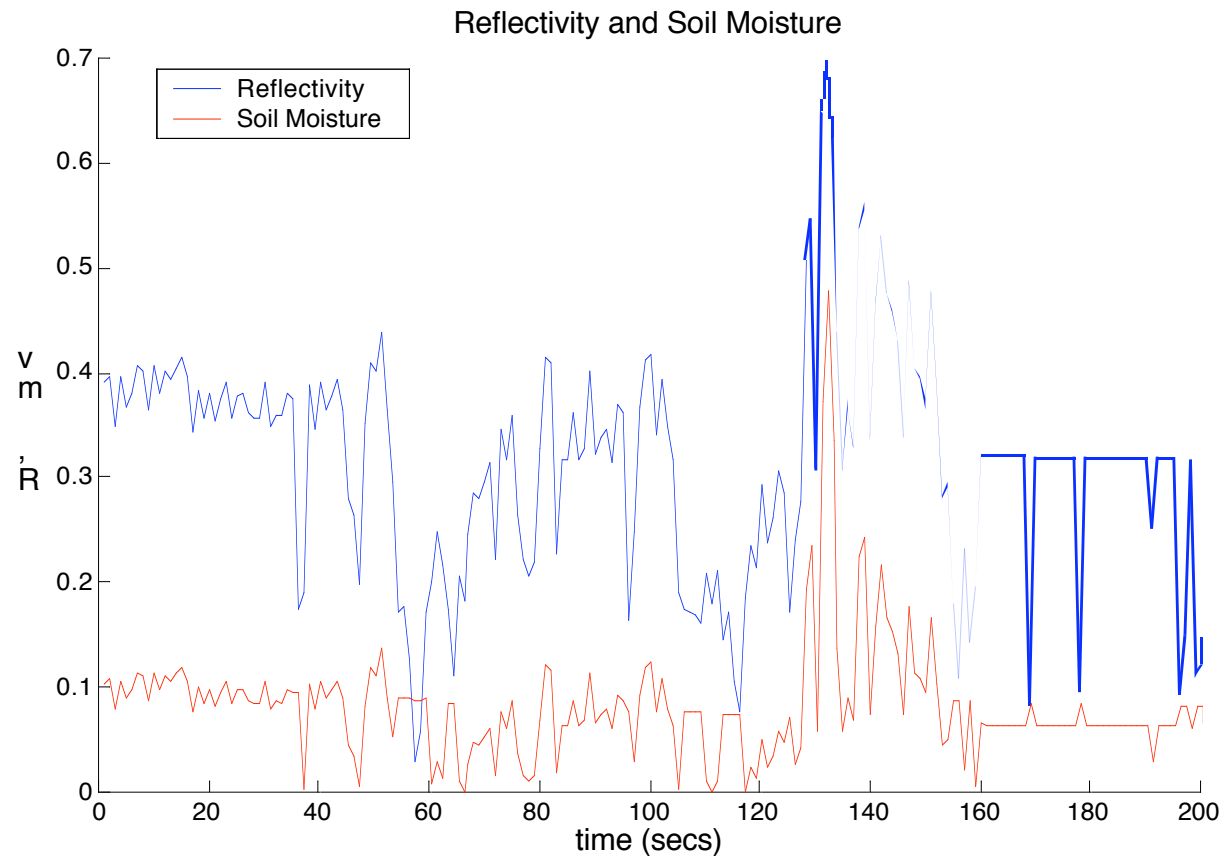
- Soil moisture over arid regions is usually low
- Little or no rain for long periods of time
- No irrigation
- Little or no vegetation cover
- Topography main parameter



# R dependence on $m_v$



- R and  $m_v$  are scaled replicas of each other
- This is a restatement of the proportionality between the two parameters



# Conclusions



- Visual interpretation of the data show that GPS signals do reflect strongly from known bodies of water and places of high soil moisture content
- Permittivity comparisons appear to indicate the existence of a soil type effect on GPS reflections
- Accuracy is TBD, but results appears reasonable
- Over places with low vegetation density soil moisture can be computed from the GPS reflections

# Open forum



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